PROGRESS TOWARDS PICOMETER ACCURACY LASER METROLOGY FOR THE SPACE INTERFEROMETRY MISSION

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Peter G. HALVERSON, Andreas KUHNERT, Jennifer LOGAN, Martin REGEHR, Stuart SHAKLAN, Robert SPERO, Feng ZHAO,
Tallis CHANG[1],
Edouard SCHMIDTLIN, Roman GUTIERREZ[2],
Thomas R. VANZANDT[3],
Jeffrey YU[4]

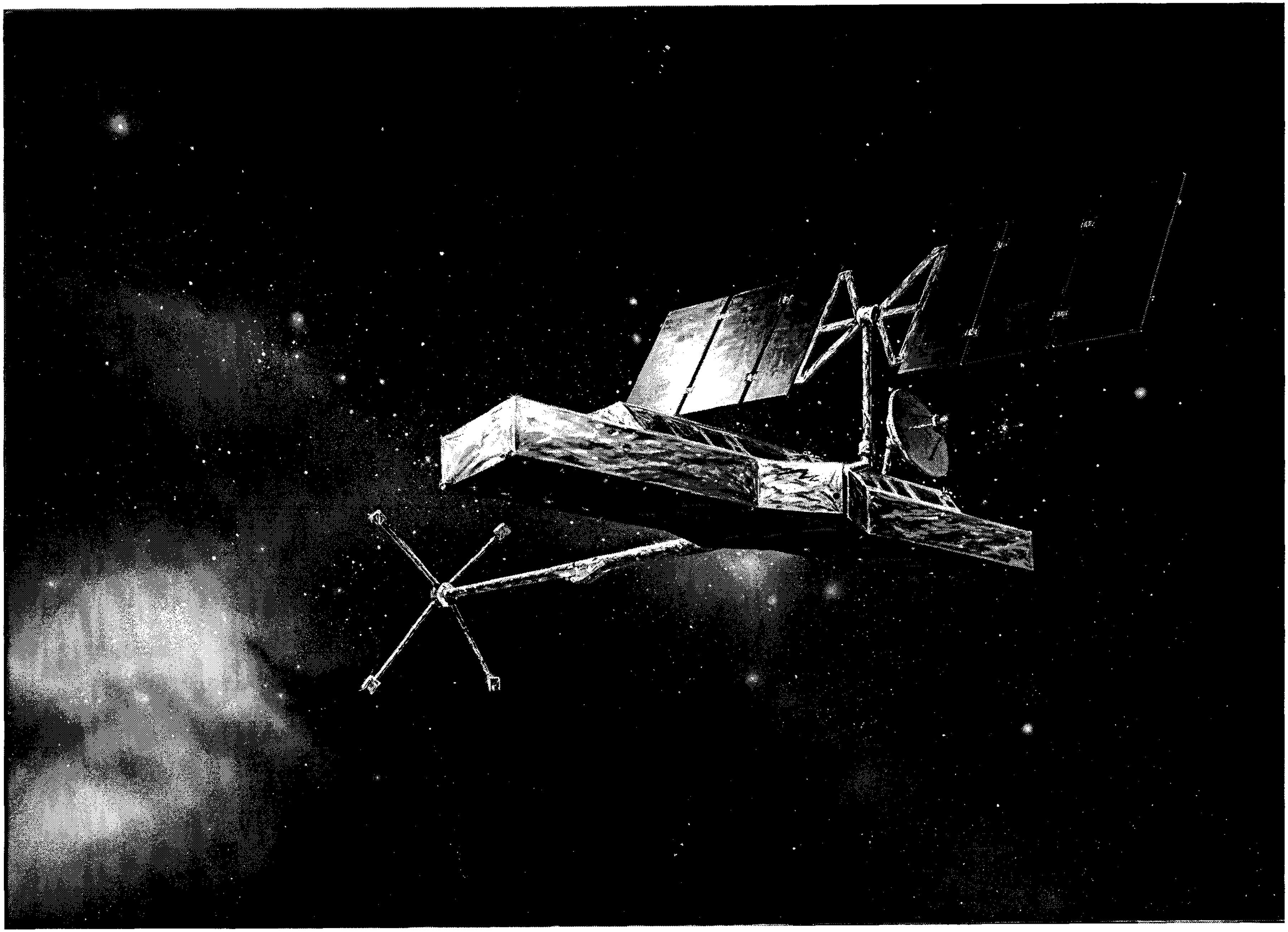
California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109. Email: halver@huey.jpl.nasa.gov

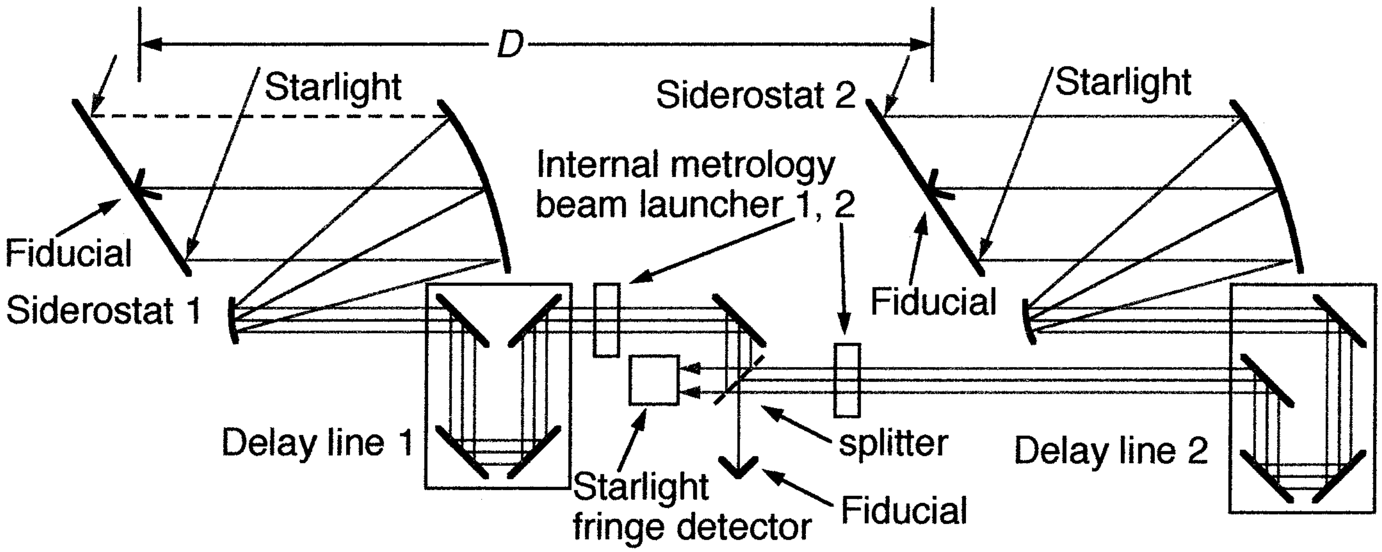
[1] Now at Chromux Technologies, Inc. 9255 Deering Ave. Chatsworth, CA 91311.
Email: tchang@chromux.com

[2] Now at Siwave Inc., 450 North Brand Blvd. #600, Glendale, CA 91203.
Email: e.schmidtlin@siwaveinc.com, r.gutierrez@siwaveinc.com

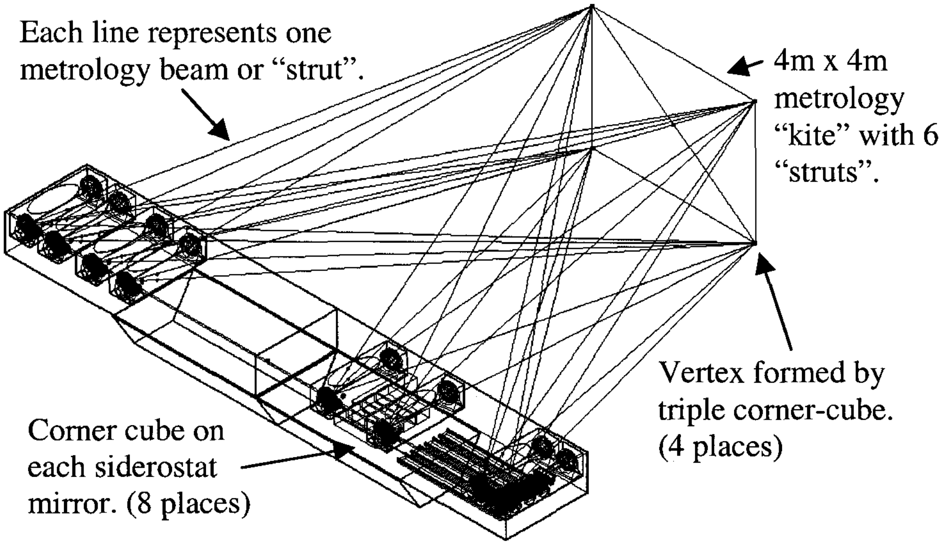
[3] Now at GEOSense, L.L.C., 115 W. California Blvd. #304, Pasadena, CA 91105. Email: tom.vanzandt@geosense.com

[4] Now at Holoplex Technologies Inc., 600 South Lake Ave, Suite 102, Pasadena, CA 91106. Email: jwyu0@socal.rr.com





Simplified sketch of SIM's internal metrology light path (red line) and starlight (blue). Internal metrology measures the difference in starlight path (adjusted by the delay lines) required to keep the central startlight fringe locked at the fringe detector. The baseline vector ***D*** is the vector from the center of siderostat 1 to siderostat 2.



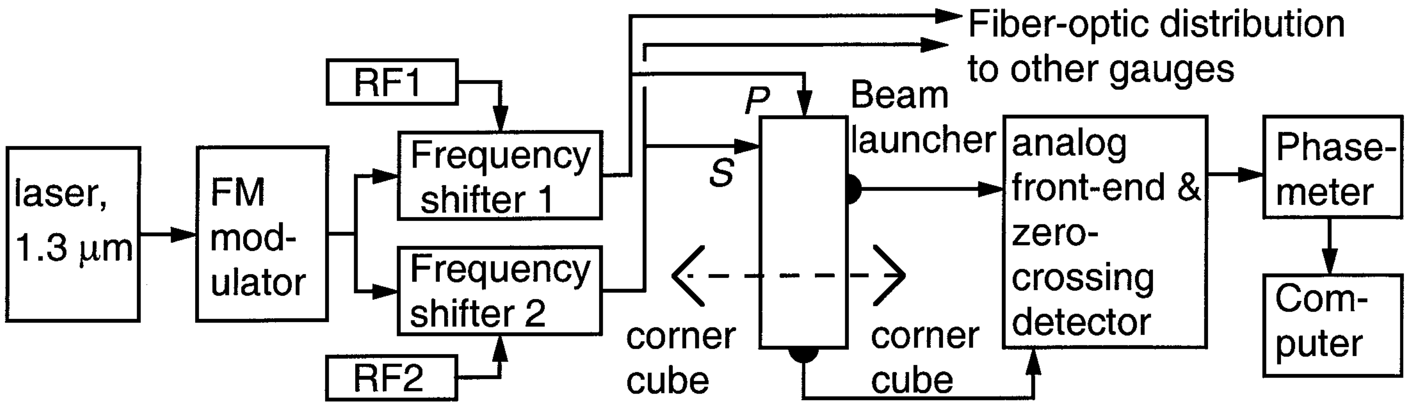
Cut-away view of SIM's optical support structure containing siderostats, optical delay lines and startlight beam combiners. The external metrology beams or "struts" will be used to monitor the geometry of SIM to ~100 pm. *Geometry* means the precise lengths, relative directions and positions of the baseline vectors of the three interferometers (one for science and two for reference stars). (The two extra siderostats are backups.)

	Internal metrology requirement	External metrology requirement
Number of gauges	8	42 (kite: 6, roll estimation: 4, siderostats: 32)
Number of gauges for mission success (assuming dispersed failures)	6 (two siderostats are spares)	24 (Kite: 5, roll estimation: 1, siderostat fiducials: 24)
Distance between fiducials	20 meters	Varies: shortest are 4 meters, longest are 12 meters.
Motion; ranges of distances	2.6 meters while changing stars; 10 microns while observing	10 microns
Velocity	2 cm/s while changing stars, 1 micron/sec while observing	
Accuracy (absolute)	Solved for with astrometric data	3 microns rms
Accuracy relative	15 pm rms (1 hour time scale); 8 pm rms (5 minute s)	
Temperature coefficient	2 pm/mK (soak); 50 pm/mK (sensitivity to gradients)	

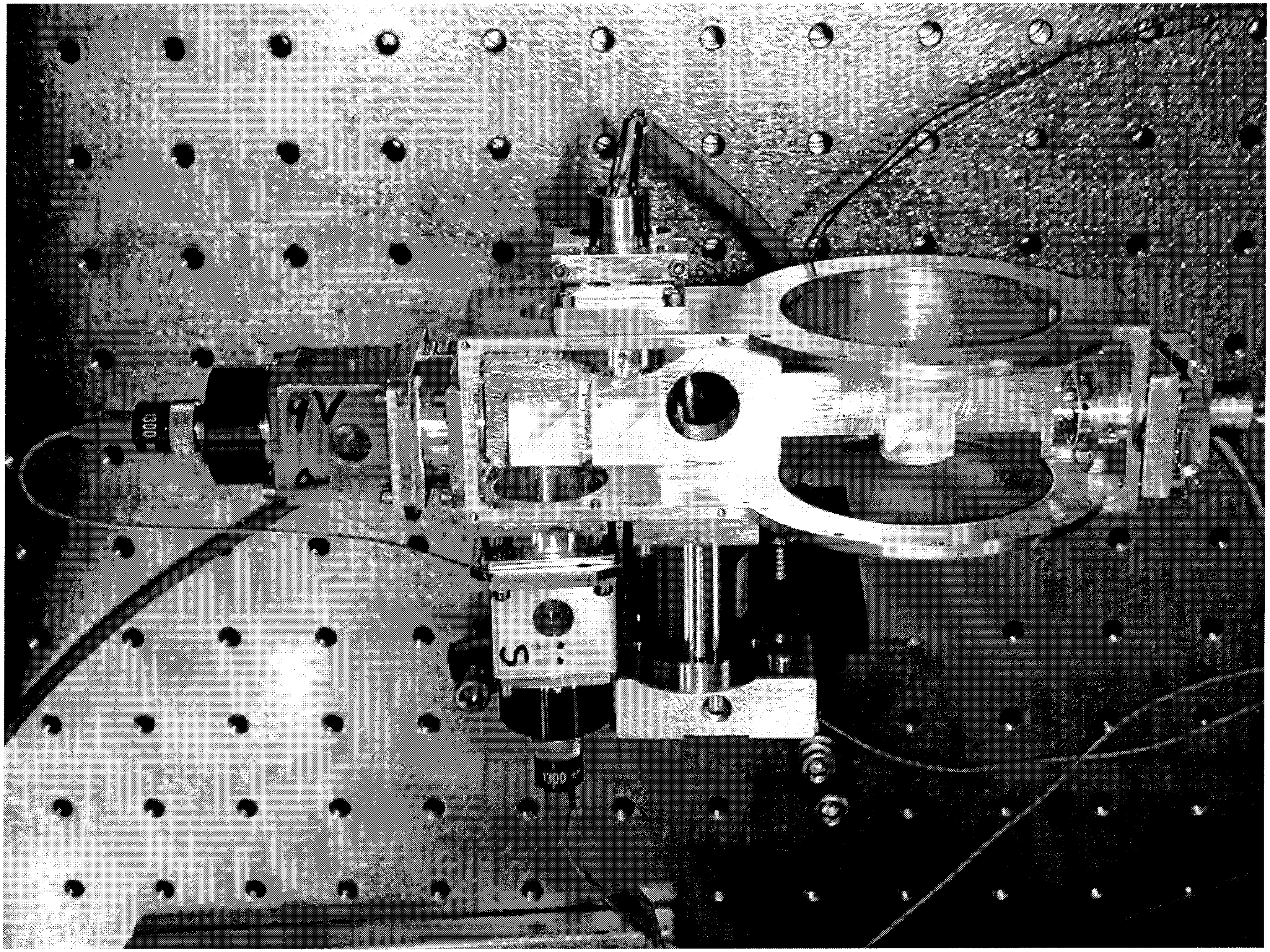
Table 1: SIM metrology requirements, subject to change as SIM's design evolves.

Wavelength	1.3 microns
Distance between fiducials	2.5 meters
Beam diameter	5 mm, measured to $1/e^2$ intensity.
Accuracy (absolute)	Not yet measured
Accuracy (relative)	~100 pm (Dominated by polarization leakage. Ignores mispointing, diffraction and thermal error sources)
Temperature coefficient	~100 pm/mK (See text)

Table 2: current performance of metrology prototypes



Block diagram of metrology system under development. The FM modulator linearly sweeps the optical frequency 84 MHz in a triangle pattern for cyclic averaging. The frequency shifters are fed by RF signals 100 kHz apart to create the 100 KHz heterodyne which will be detected by the photodiodes (attached to the beamlauncher).


9V
S
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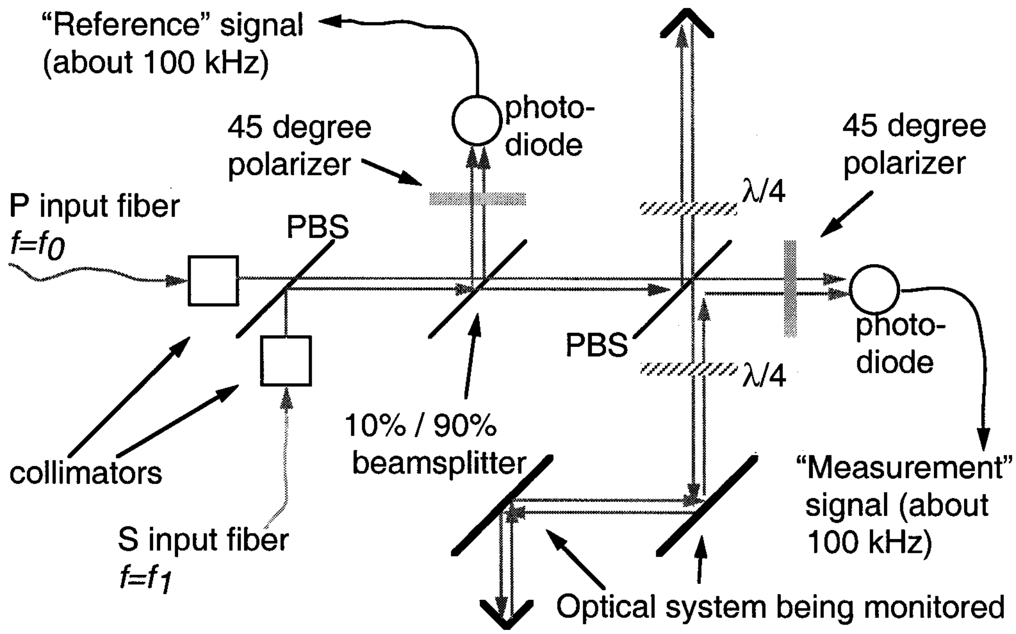
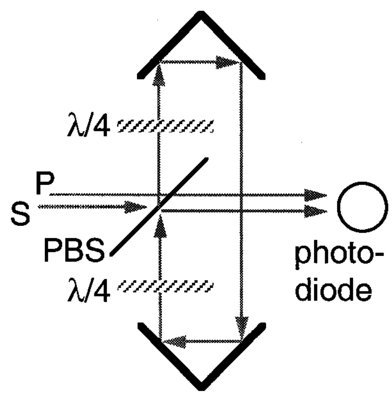


(A) Signal path of beamlauncher. S light is in red, P light is in blue.



(B) Alternative "racetrack light path.

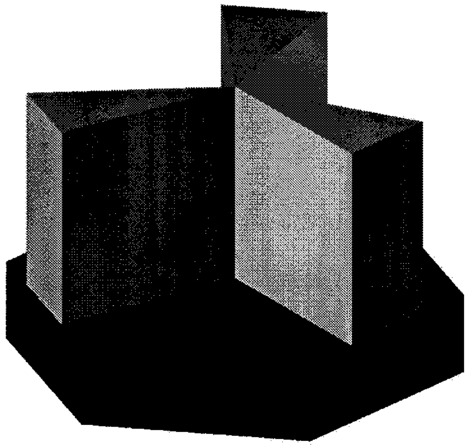
	Goal	Achieved
Dihedral error	<2 arc-seconds (as)	~2 as
Planarity of faces	<λ/100 peak/valley (633 nm)	<λ/30 p/v (633 nm)
Vertex-to-siderostat surface distance.	<1 micron	0.8 micron
Vertex-to-siderostat distance calibration	2 nm	~150 nm

Table 3: performance of siderostat fiducials, expressed as surface errors.

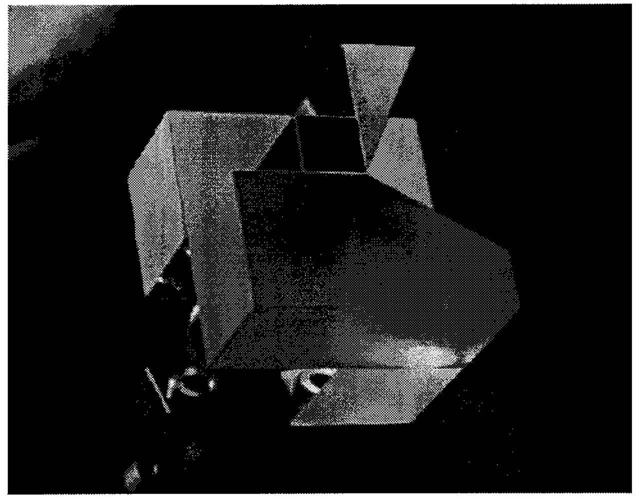
	Goal	Achieved
Dihedral error	<λ/20 p/v (633 nm) (<1 as)	1 as
Planarity of faces	<λ/20 p/v (633 nm)	<λ/20 p/v (633 nm)
Co-location of corner-cube vertices	<10 microns	2 microns
Vertex co-location calibration	200 nm	Not measured

Table 4: performance of external metrology fiducials (triple corner-cubes).

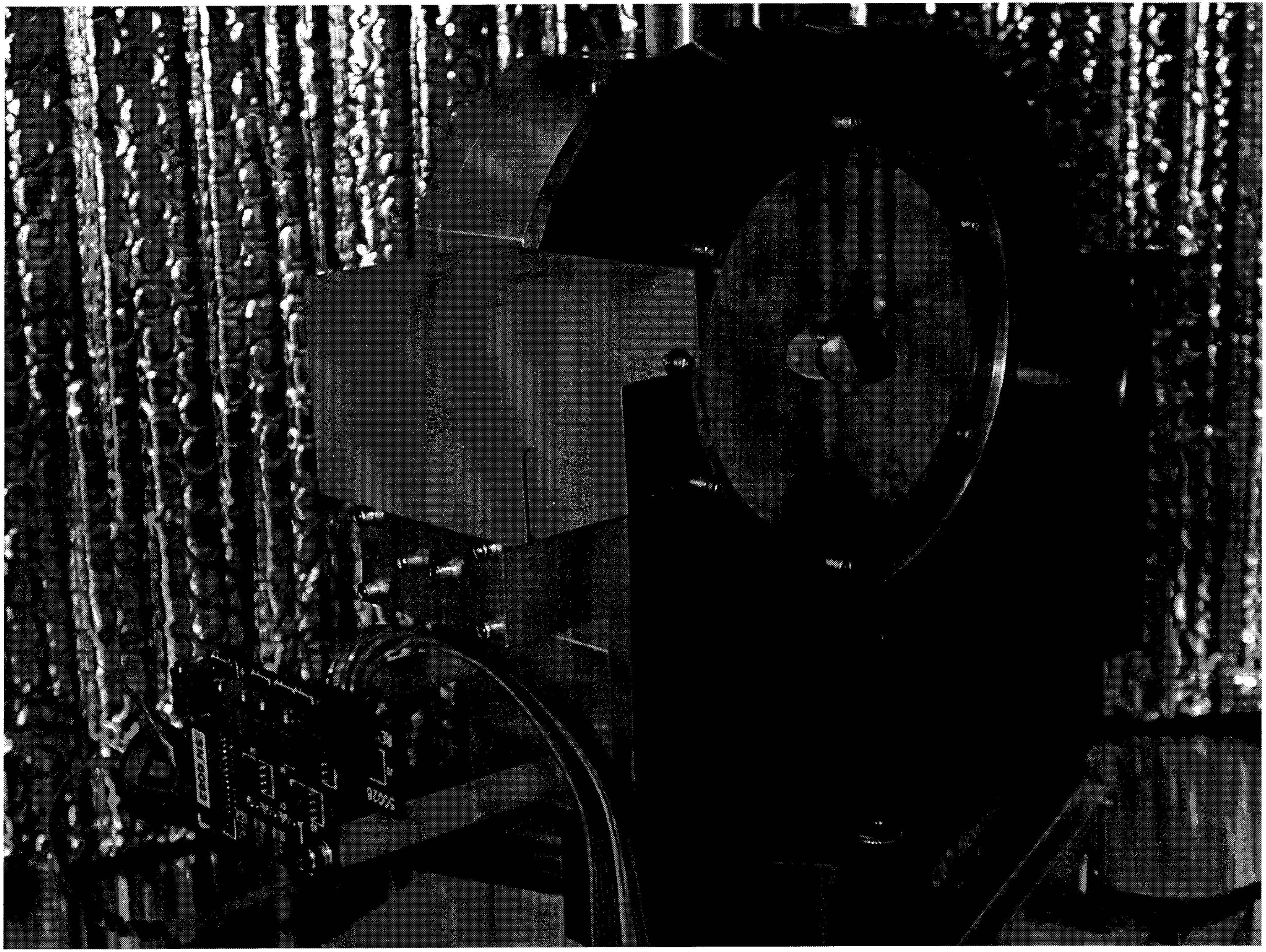
Metrology Fiducials



SIM Triple Corner Cube



Prototype TCC



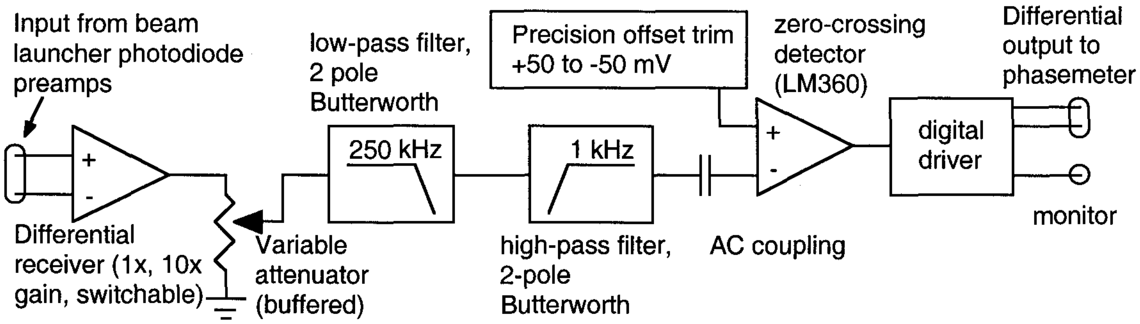
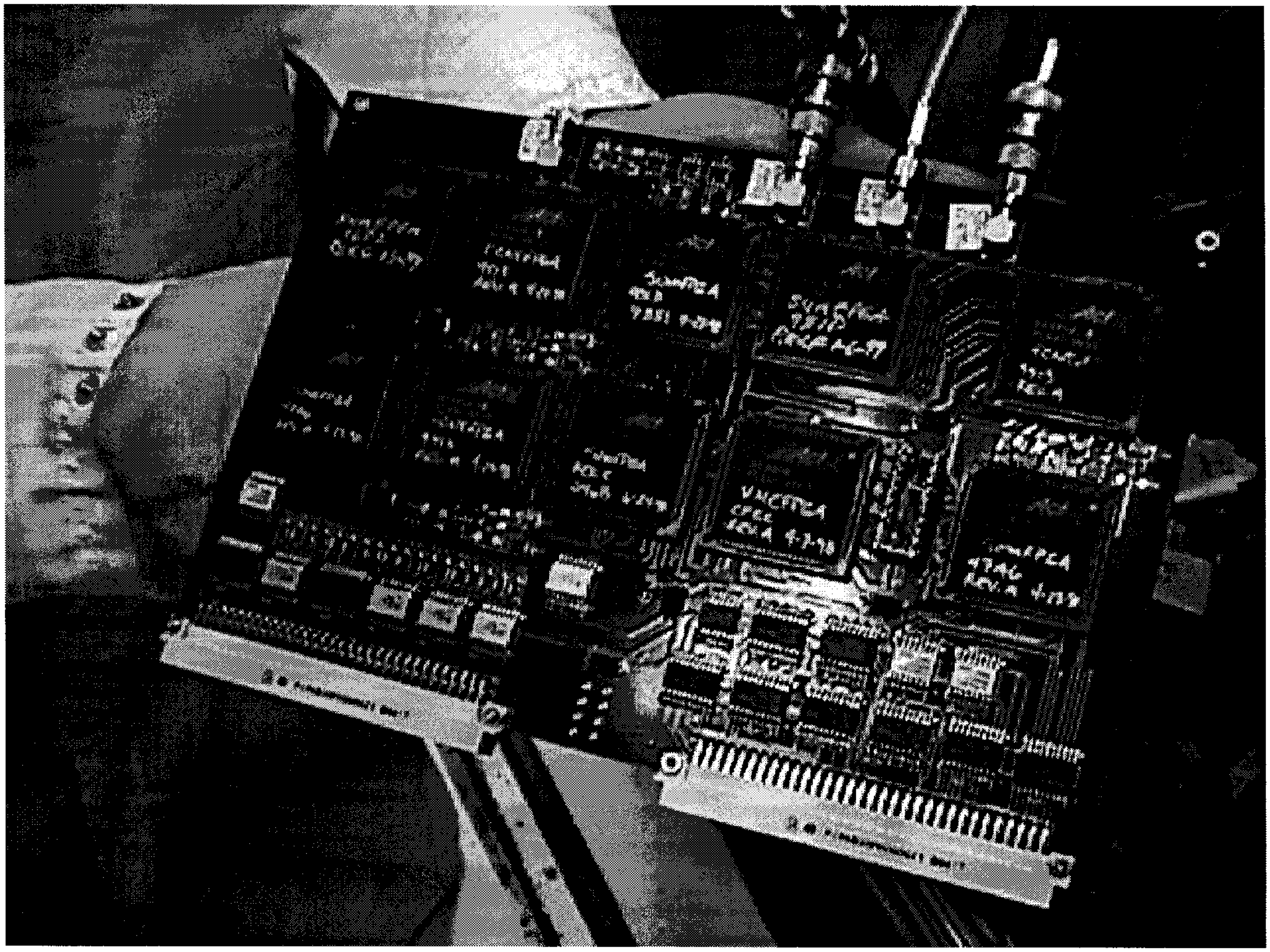


Figure 6: Analog front-end used to convert heterodyne signal to square wave.

No. of channels:	6 (supports 3 metrology gauges.)
Input --> output	100 kHz sine, +/- 10 V FS --> differential TTL
Drift:	1.8 μfringe (1.2 pm) in 6 hours at 100 kHz
Noise:	35 μfringe at 5V into zero-crossing detector. 0.1 μfringe, at 1 sec integration time
A.M. rejection:	1 μfringe (0.65 pm) for 10% amplitude change (balanced common mode). 4 μfringe (2.6 pm) for 10% amplitude change (unbalanced).
Crosstalk:	<0.02 % amplitude artifact observed on one channel, with 5 other channels driven in tandem. (2 pm)

Table 5: Performance of 100 kHz post-amp electronics.



Number of channels	6
Maximum clock frequency	128 MHz.
Stability	10^{-5} cycles (6.5 pm) for ambient temperature held to 0.1 C.
Range	$2^{32} = 4.3\text{x}10^{9}$ cycles. (2795 meters)
Het. frequency range	1954 Hz to 1.33 MHz
Phase resolution (no averaging)	$1.6\text{x}10^{-5}$ cycles (10 pm) at 2 kHz to 0.01 cycles (650 pm) at 1.3 MHz heterodyne frequency. (Improves with averaging)
Velocity range at maximum heterodyne frequency	+/- $0.88\text{x}10^{6}$ cycles per second (0.58 meters/second)
Temperature sensitivity	<500 picoseconds/C (32 pm/C)

Table 6. Specifications for the JPL phasemeter. Specifications in picometers assume a 100 kHz heterodyne frequency and 1.3 micron wavelength.

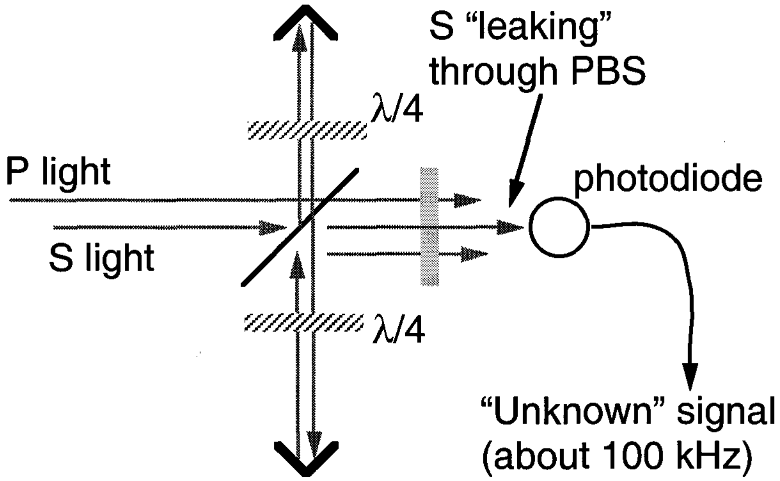


Figure 7: Schematic of polarization leakage problem. A small amount of S polarized light "**leaks**" through the polarizing beam splitter (diagonal line) and interferes with the S light that makes the round trip between corner cube fiducials.

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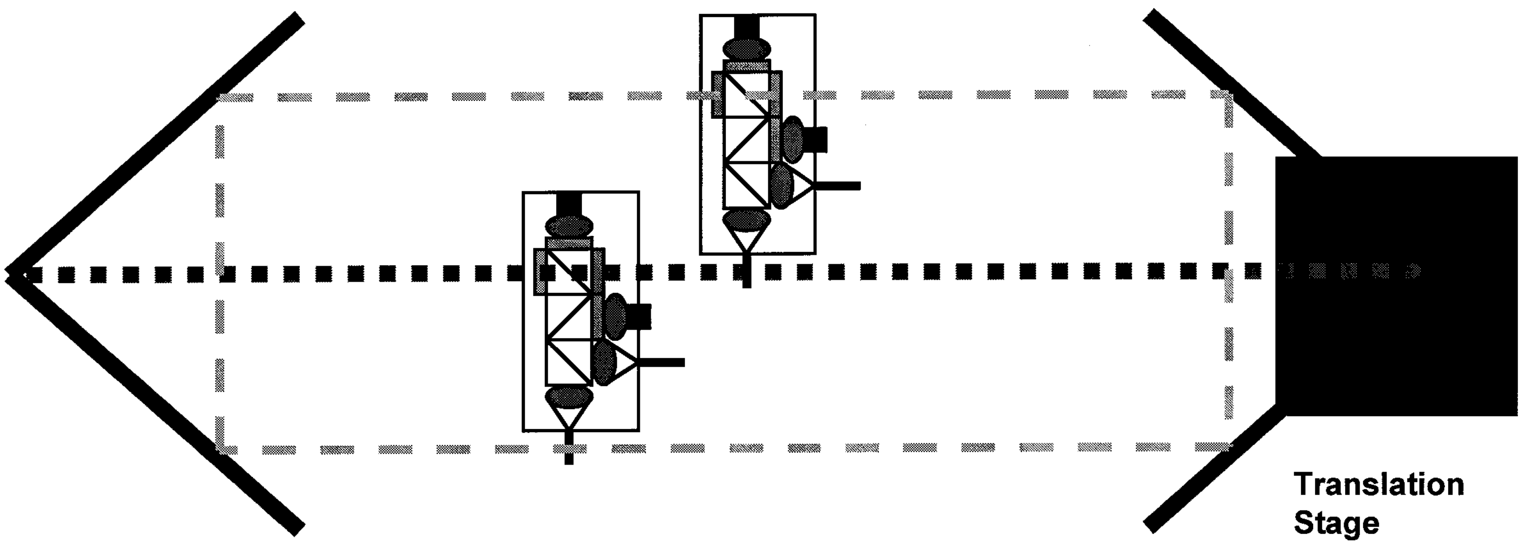
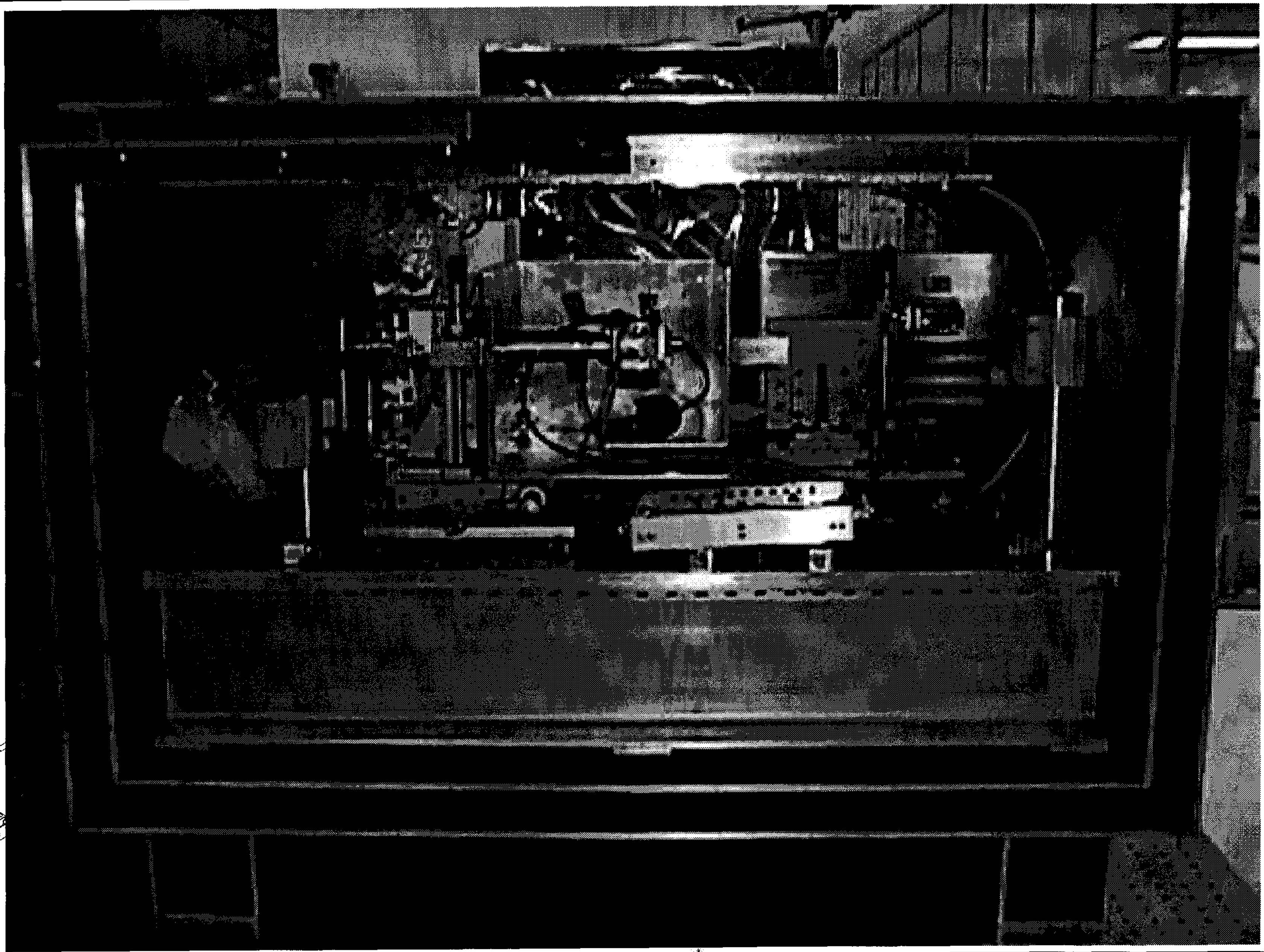
- Two gauges measuring between common corner cubes
- One race track, one vertex-to-vertex
- Consider one gauge as truth, measure second gauge's performance against it
- Use of two gauges gives good common mode rejection.



2-Gauge experiment (not yet in vacuum chamber)



Beamlauncher (in thermal shield)

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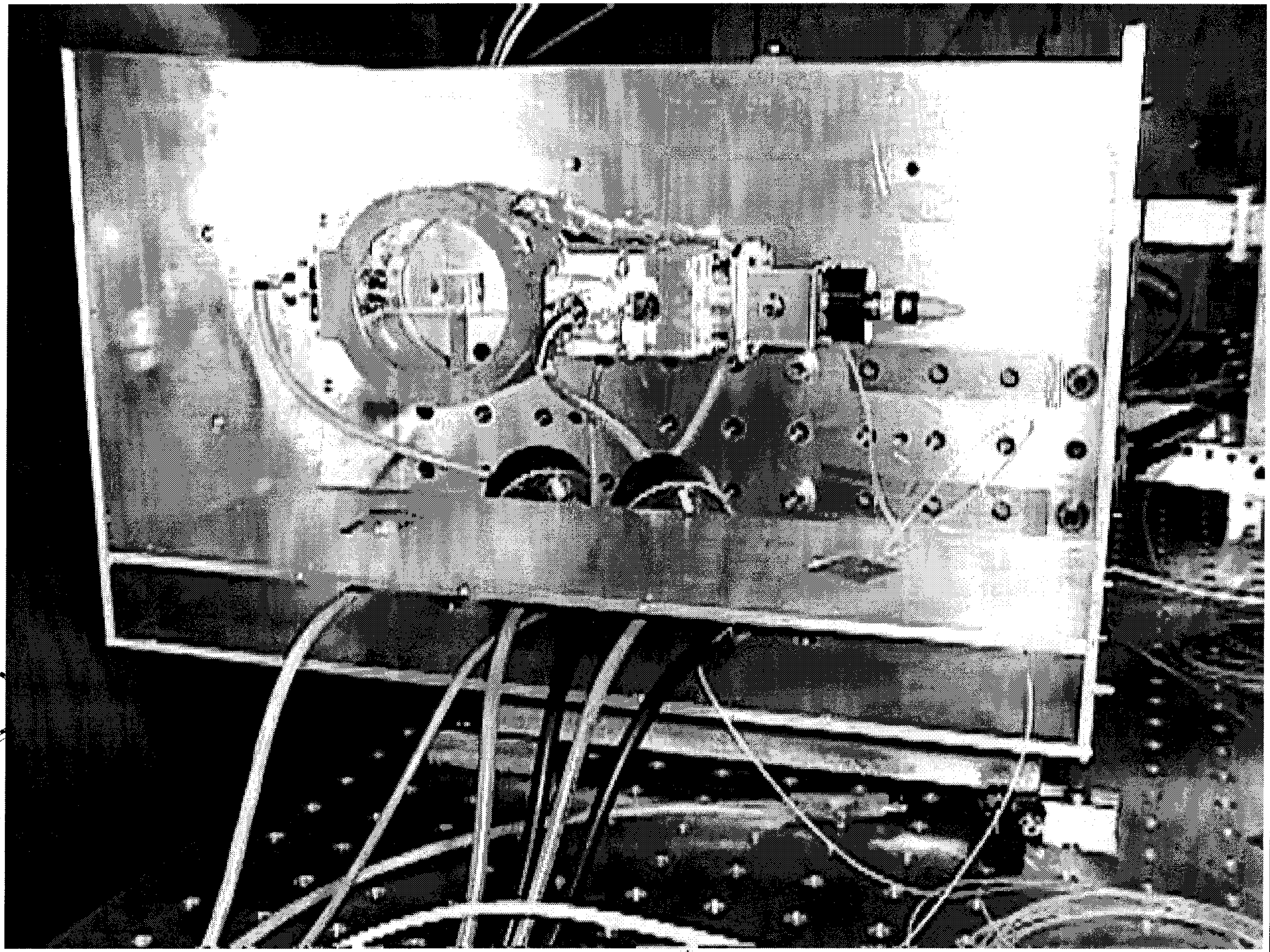
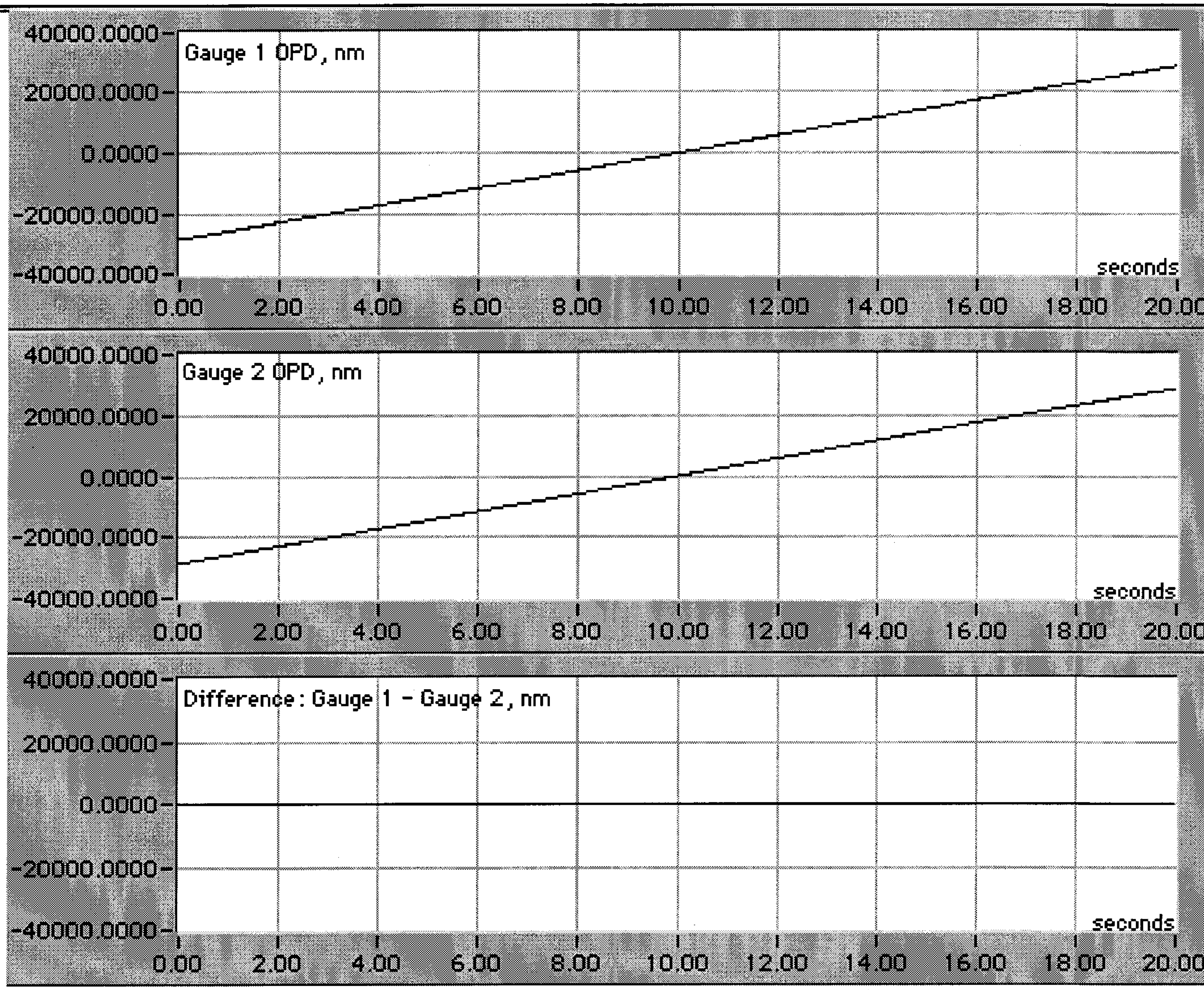
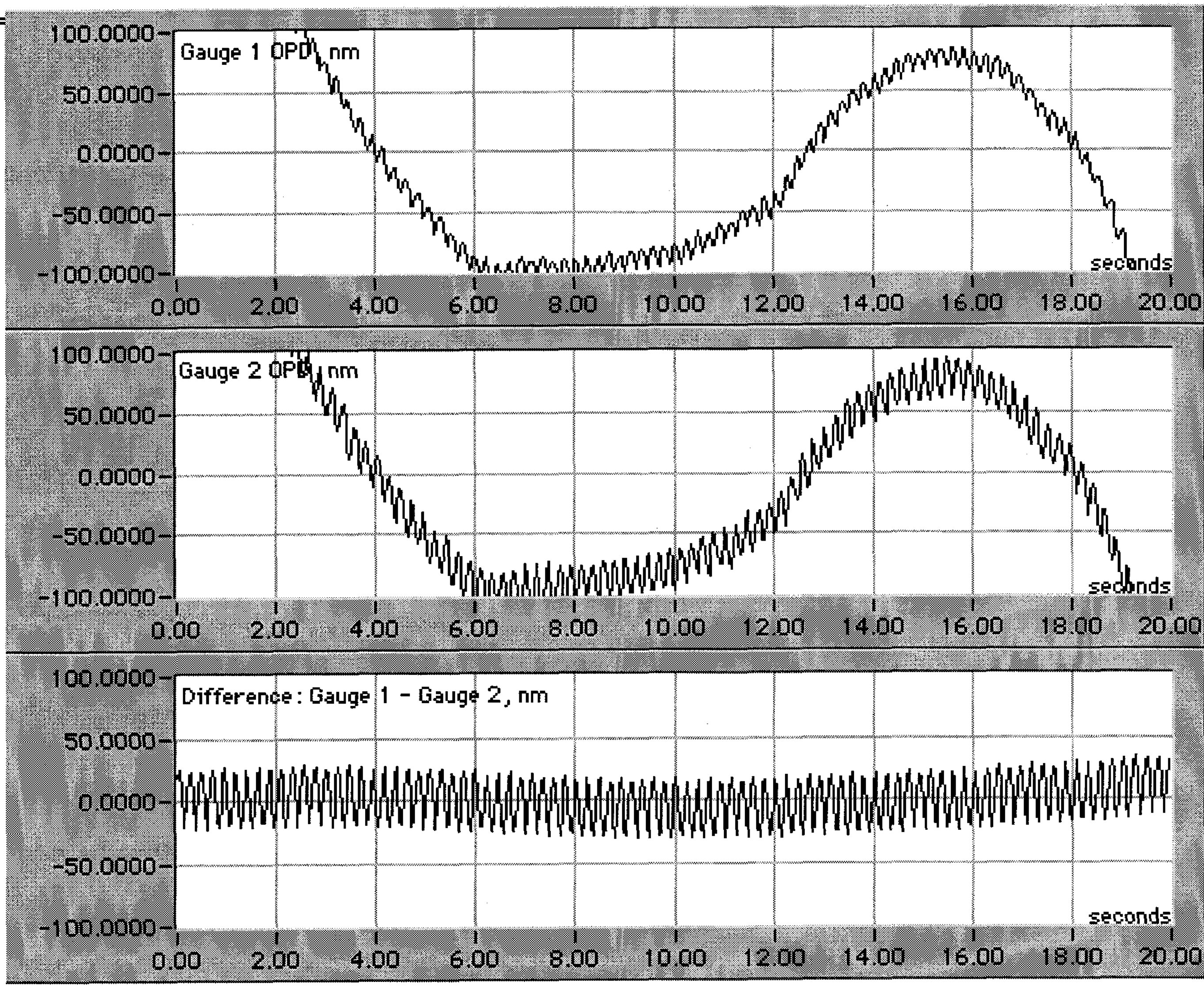


Sample Data (from 2000_06_29_18_baseline/a)



- Corner cube moved linearly 57.2 microns in 20 seconds
- Two gauges agree closely. Next slide will look closer...

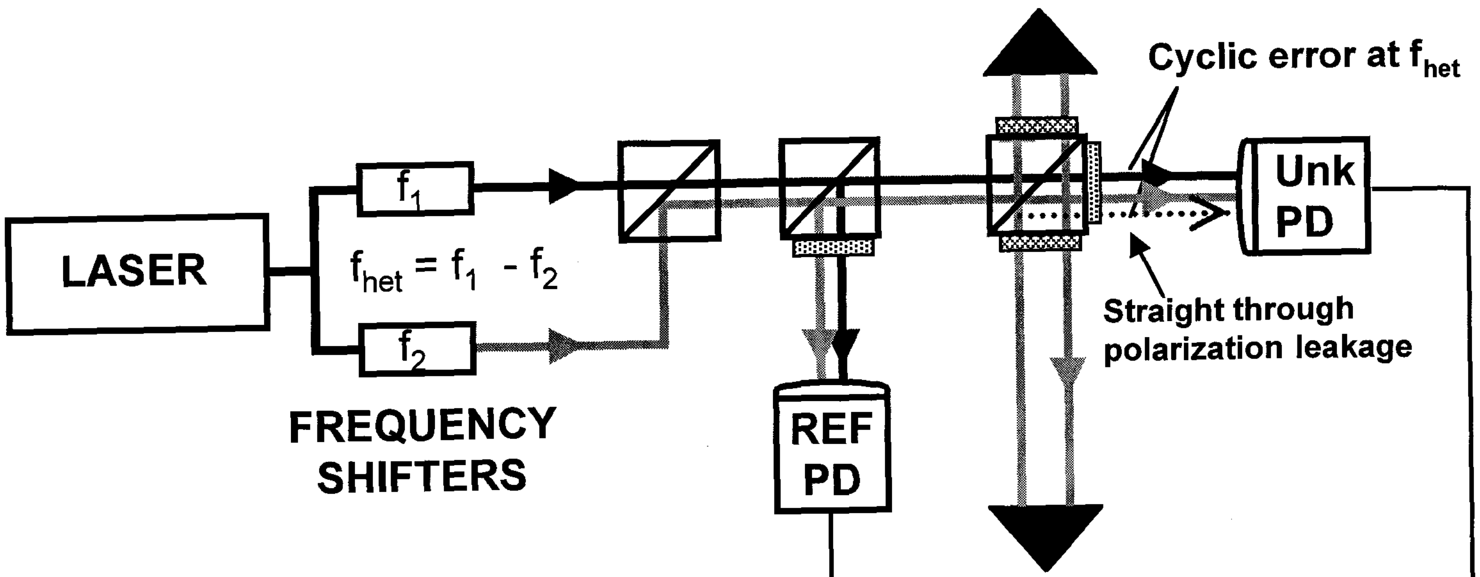
Same data, but detrended and rescaled

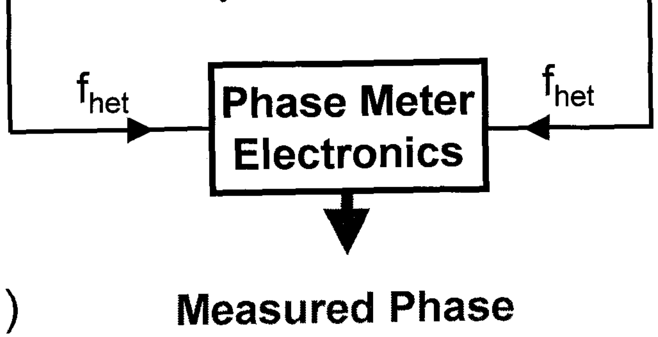


Slow, common-mode deviations from linear sweep are caused by corner cube piezo non-linearity (not a problem.

Fast oscillating deviations are caused by polarization leakage: the infamous cyclic error. Error magnitude: 14.5 nm RMS in difference.

Cyclic Error - The Problem

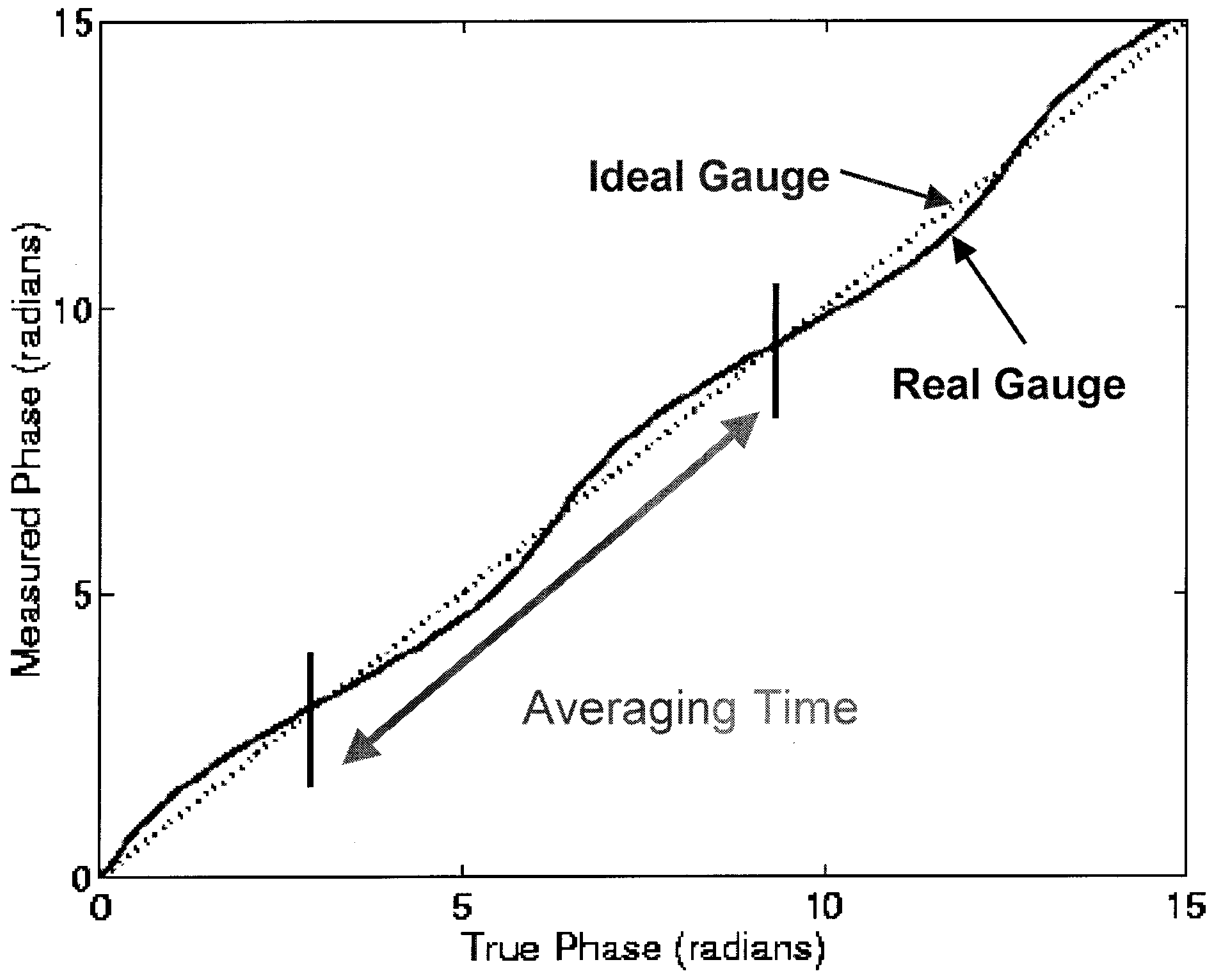




- Cyclic Error - heterodyne beat with wrong phase
- Effect: limits phase resolution
- Cause: Polarization leakage
  - Straight through (shown)
  - Second round trip etc

  Stray reflections

Cyclic averaging: a means to suppress cyclic error



Error is periodic => Can average it out by dithering the gauge phase over exactly one cycle.

Implementing cyclic averaging

- Gauge phase dithered by modulating laser frequency at some "reasonably high" frequency, e.g. 100 Hz
- Need full cycle of phase on shortest length i.e.

$$\Delta f = \frac{\Delta L}{L} f = \frac{c}{2L}$$

- Shortest baseline on SIM and in tech program was 2m (now 4 m for SIM) => $\Delta f = 75$ MHz
- Currently achieved by double passing through AOFM (actually applies $\Delta f = 84$ MHz)

<u>Let's apply this method to the data at hand:</u>

- Apply triangle laser frequency dither: Dither rate= 25 Hz

Cyclic averaging pattern applied to data

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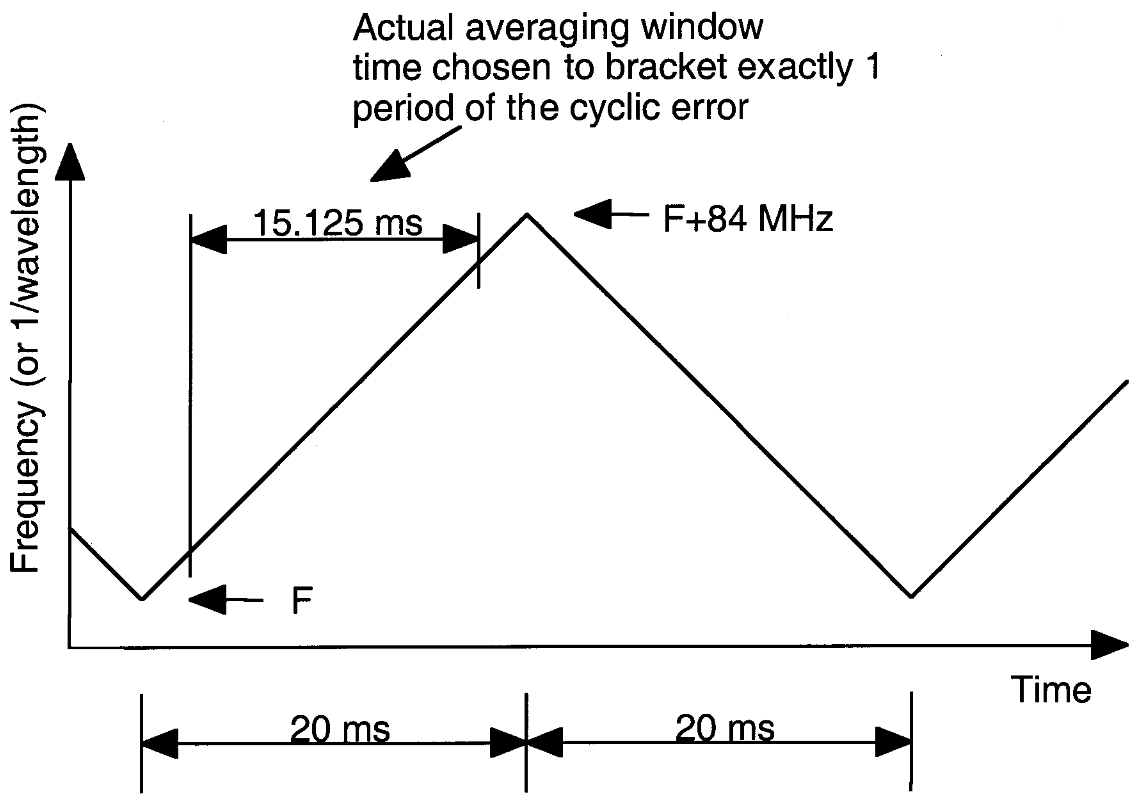
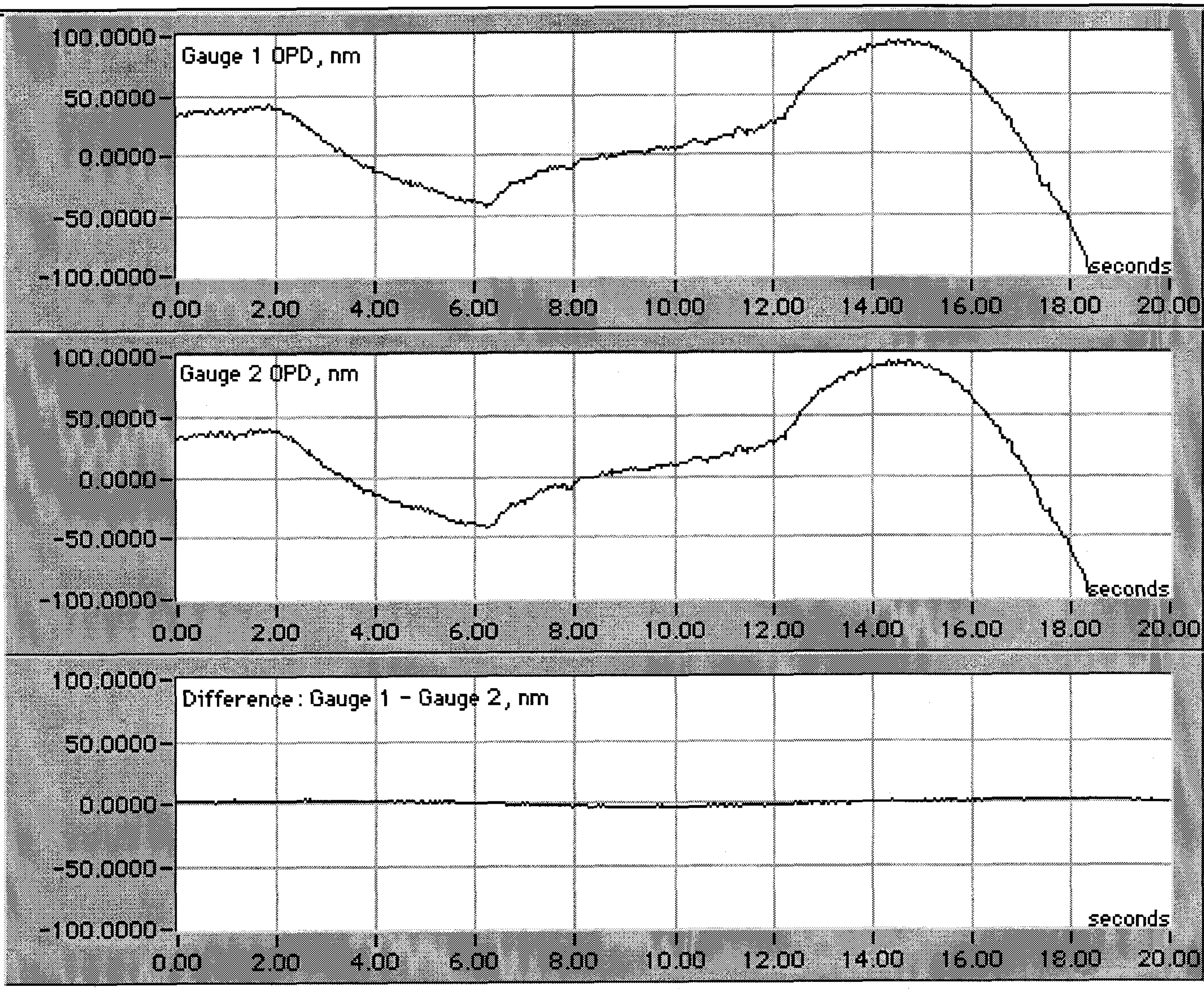
25 Hz FM dither pattern applied by AOFM



(F=base laser frequency=c/λ=227 THz)

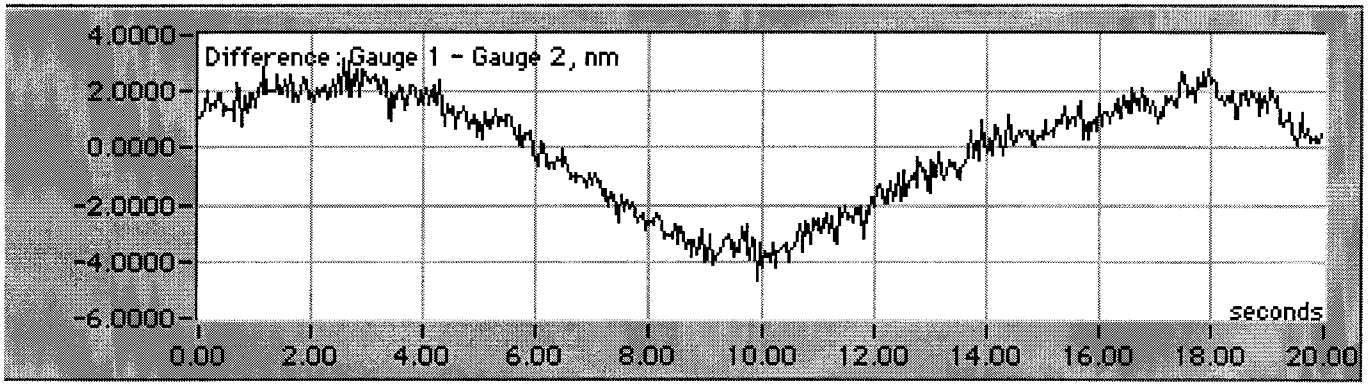
Turn on frequency dither & cyclic averaging and take new data 2000_06_29_18_baseline/b



Same setup, same scale as previous data.

Lets take a closer look...

Difference data, zoomed



Same setup, as previous data, but rescaled

Cyclic averaging reduced cyclic error from 14.5 nm down to 50 pm RMS (in the difference).

Suppression factor=14,500 pm / 50 pm = 290

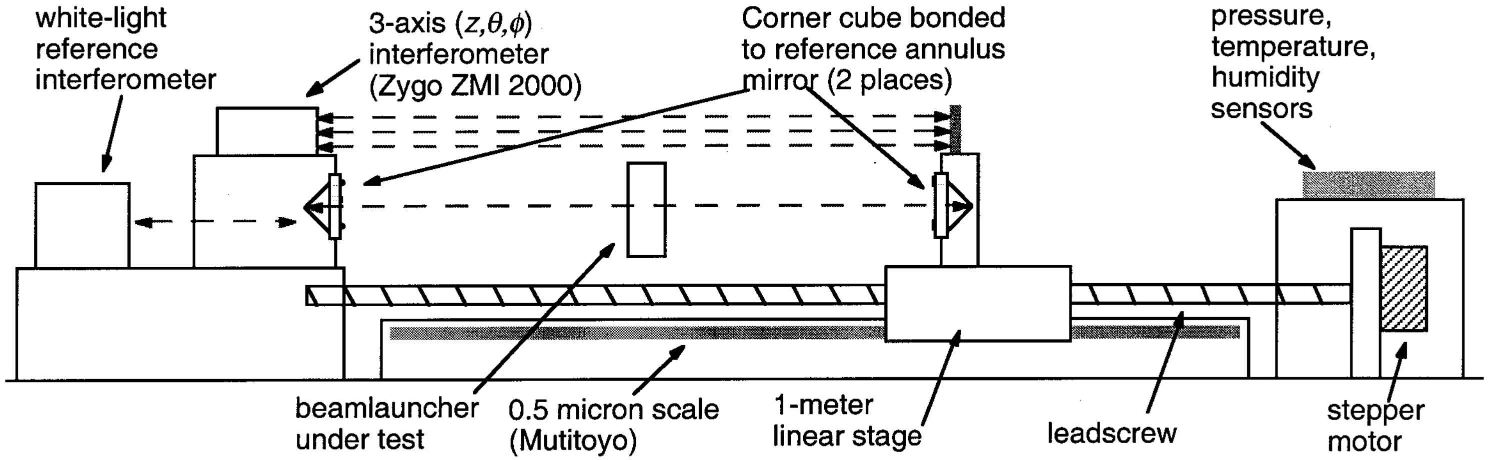


Figure 10: Layout of absolute calibration stand.

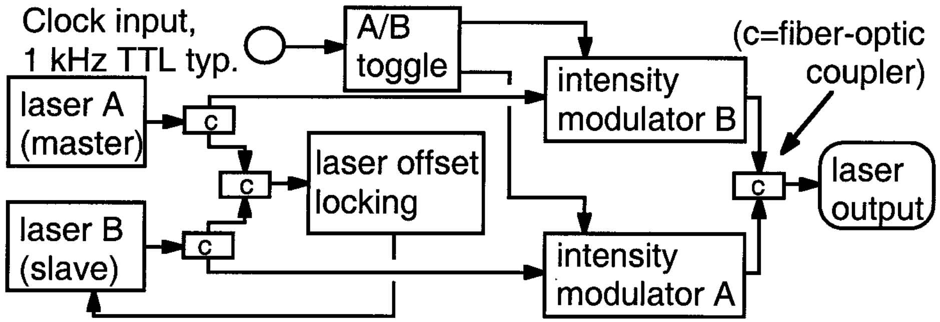
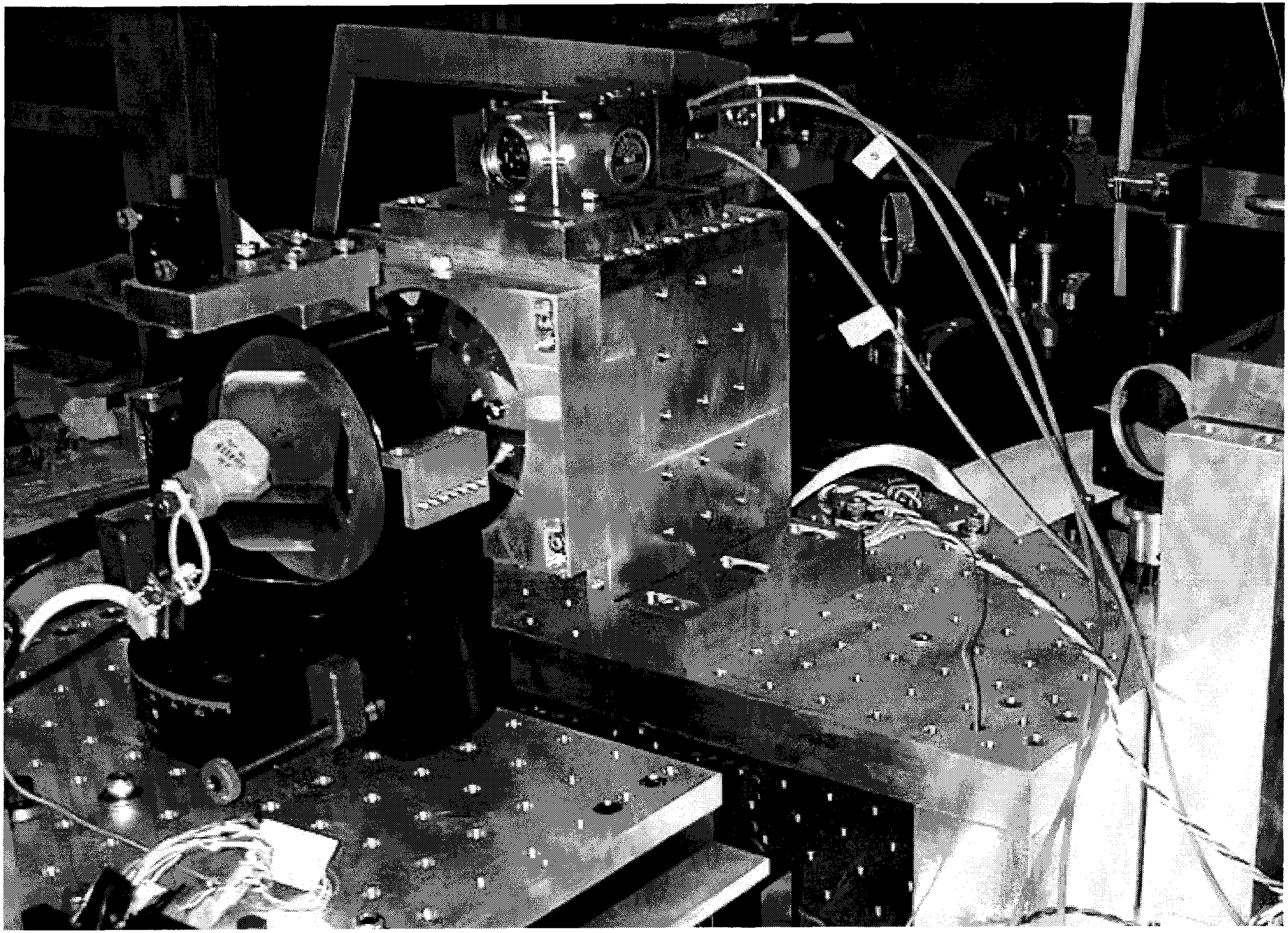
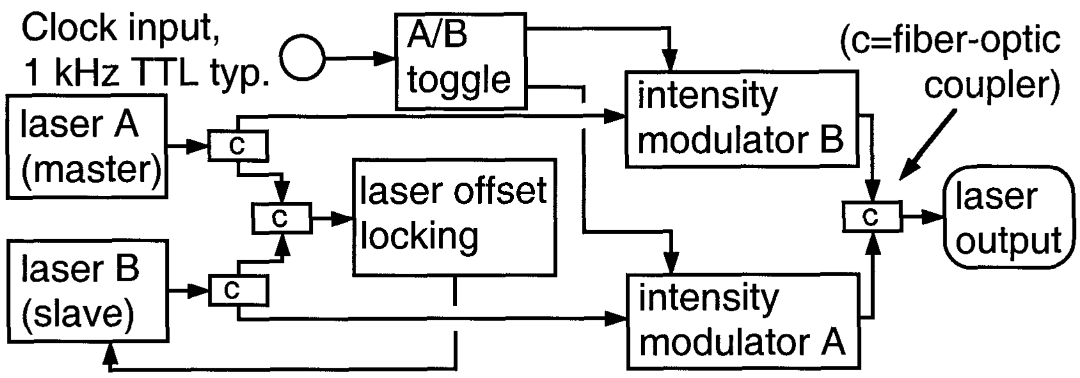


Figure 9: Laser source upgrade for absolute metrology. Light from lasers A and B are held 15 GHz apart by the laser offset locking electronics. A clock signal (in practice, the phasemeter readout clock) toggles intensity modulators A and B. The resulting 500 Hz rate, 15 GHz amplitude FM is fed to the metrology gauge for absolute calibration, as described in the text.





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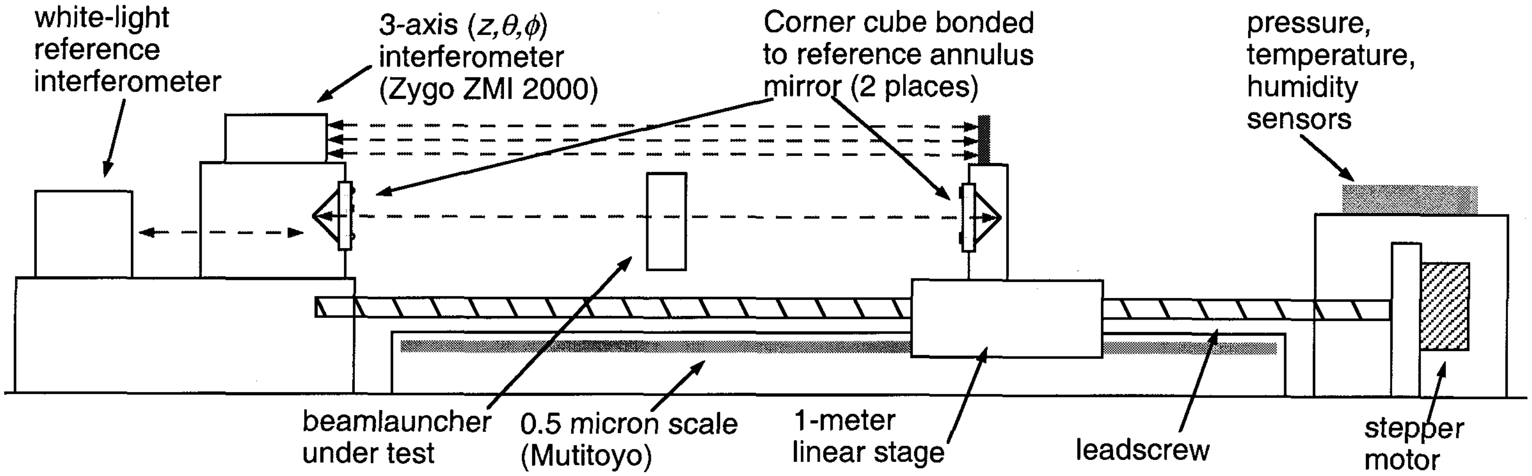
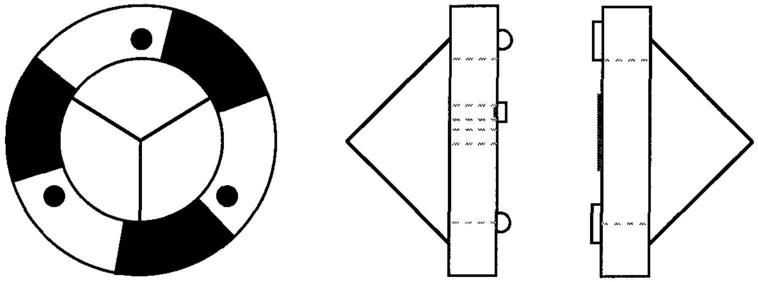


Absolute metrology calibration stand.



End view

Side view

Reference annulus & corner cube

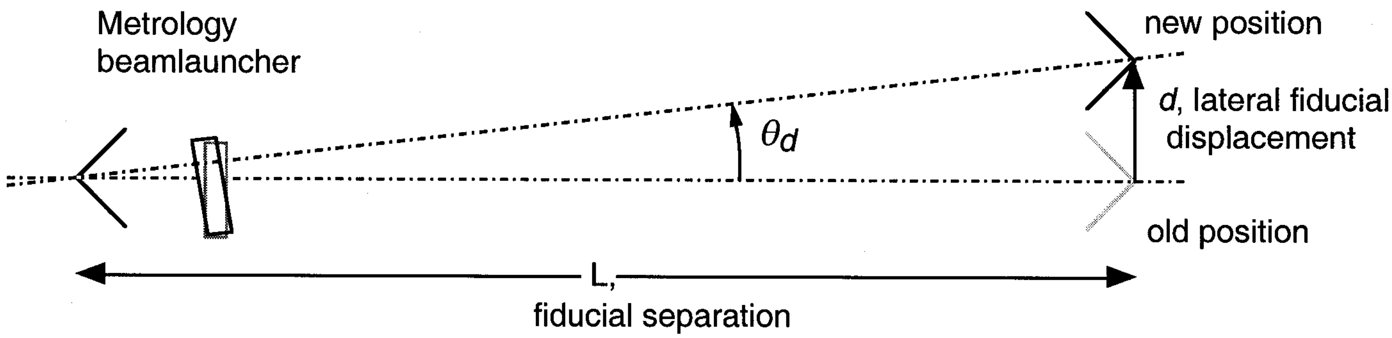


Figure 11: schematic of a disturbance moving a fiducial, requiring a beamlauncher pointing angle change θd to maintain alignment.

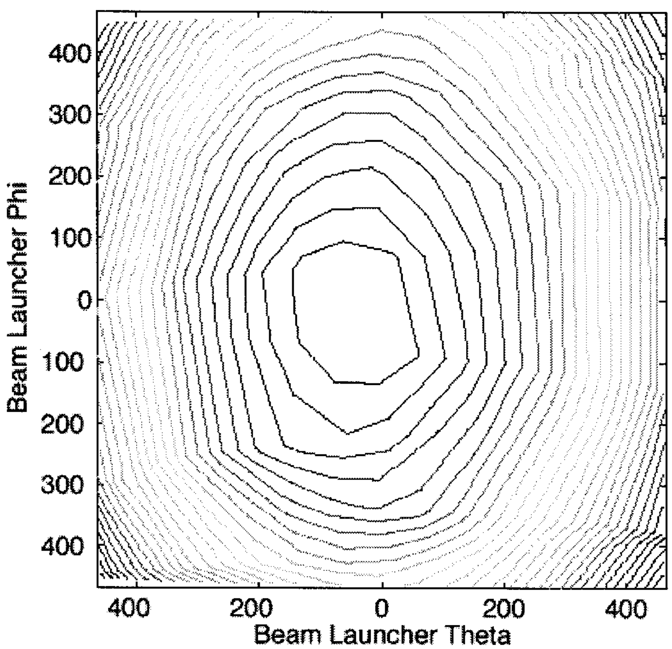


Figure 12: phasemeter output (L) as a function of beamlauncher elevation and azimuth angle. Each contour is 0.002 cycles or 1.3 nm. The central region, near perfect alignment, has a *maximum* in L. $L \approx 2$m. Theta, phi: arbitrary units.

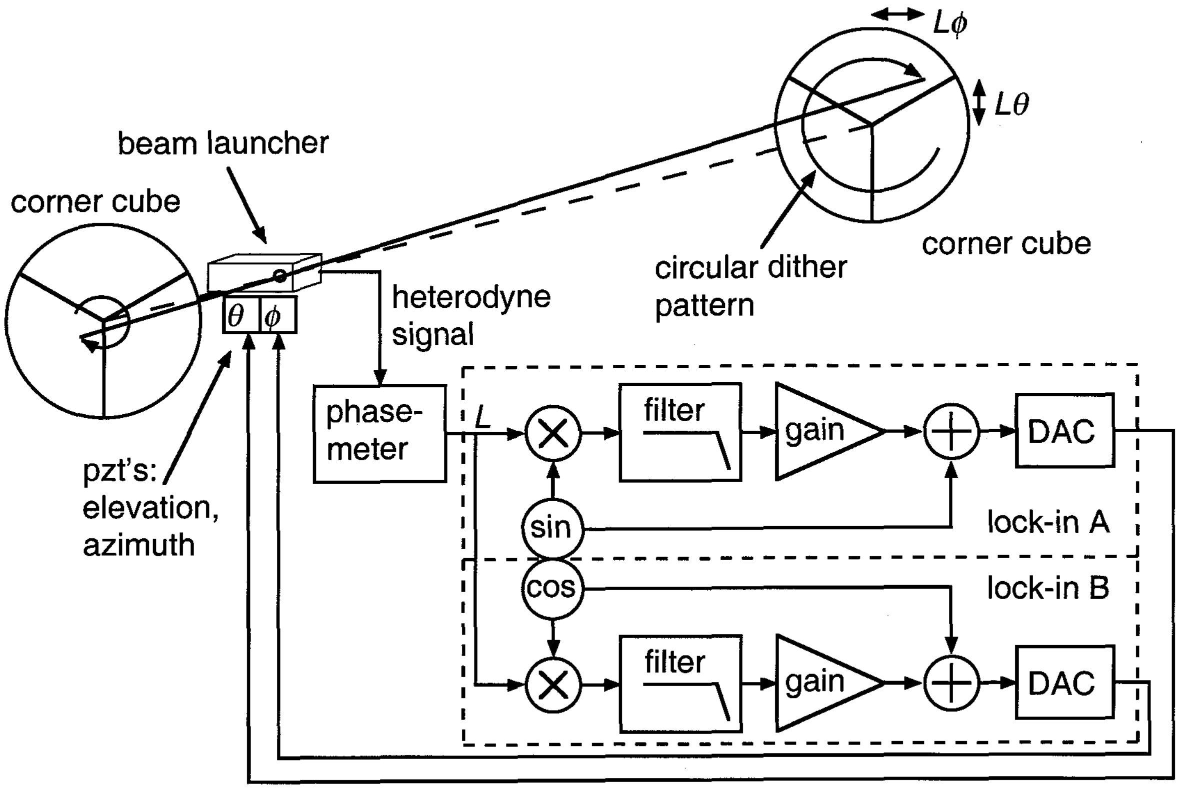


Figure 13: schematic of beam launcher steering in two orthogonal directions θ and ϕ, controlled by dual lock-in amplifiers.

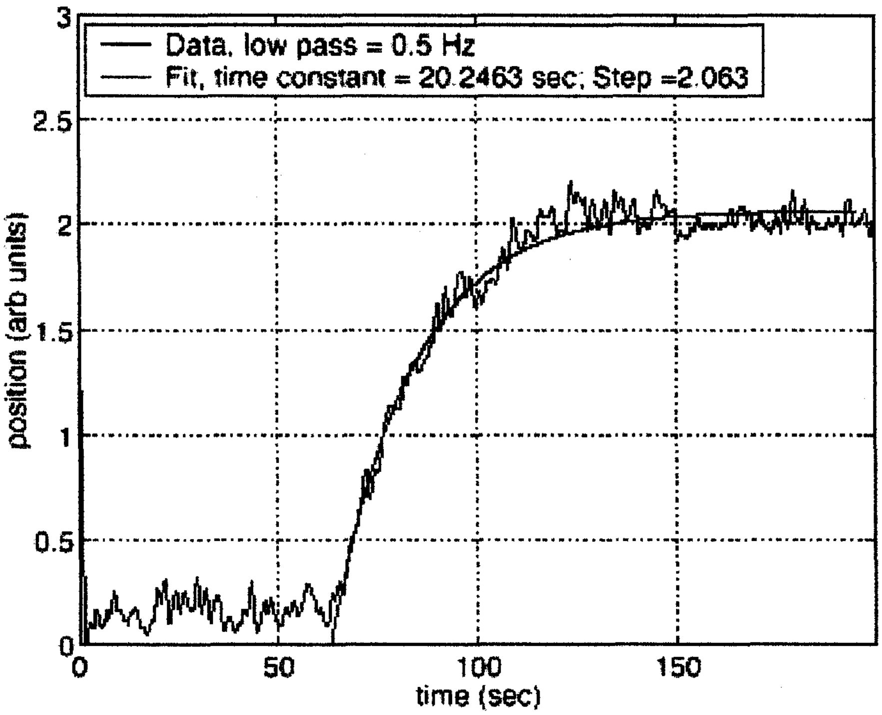


Figure 14: Recovery from a d=110 micron displacement of a corner cube fiducial. L=2 meters. Dither frequency = 50 Hz. Data taken in air.